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Citation for published version:

Shek, J, Dorrell, D, Hsieh, M, Lin, I-H, Mostafa, K, Mueller, M & Yeh, Y-H 2013, Unbalanced Forces in Electrical Generators for Wave and Tidal Devices. in *European Wave and Tidal Energy Conference*.

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Early version, also known as pre-print

Published In:

European Wave and Tidal Energy Conference

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Unbalanced Forces in Electrical Generators for Wave and Tidal Devices

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Abstract— Electrical generators and other drive train components experience significant varying loads in wave and tidal devices. This can lead to bearing failure due to unbalanced forces caused by misalignment and rotor eccentricity. For wave and tidal devices to operate effectively components, such as bearings, should be repaired or replaced prior to failure. This paper presents modelling of an electrical generator to investigate the unbalanced forces produced and the experimental test rig design that will verify simulation work. Work from the paper will lead towards a drive-train bearing wear model where unbalanced forces can be reduced and failures minimised.

Keywords — Wave energy, tidal current energy, electrical generators, unbalanced forces, force measurement

I. INTRODUCTION

Marine energy is one of the fastest growing sectors in the energy market and continues to grow annually despite recent global financial decline. As countries aim to meet renewables targets, marine energy becomes ever more important due to its potentially high contribution towards electricity generated by renewable means. From the wind industry it is apparent that the cost of installation and operation of wind farms offshore has been expensive. This is due, in part, to the early-life failures related to the drivetrain in wind turbines [1]. Although it is not the most common cause of failure, the drivetrain, including the gearbox and generator, has the highest downtime compared with the downtime caused by the failure of other wind turbine components, as shown in Fig. 1 [2]. This inevitably leads to lost revenue and increases the cost of electricity produced. As an emerging technology, this is something that the marine energy sector must learn from.

Drive train related failure is typically linked to bearing wear, caused by misalignment in the drive train. An unbalanced magnetic pull (UMP) is produced due to an asymmetric air gap in the electrical generator, which can further increase wear.

Reduction of UMP would greatly reduce bearing loads and subsequently reduce bearing wear. For marine energy devices, it is essential that components are replaced or repaired prior to failure since a failed component can cause other components or other parts of the systems to fail. Hence, upon detection of

imminent bearing failure it is desirable to reduce UMP in order to increase time-to-failure [3].

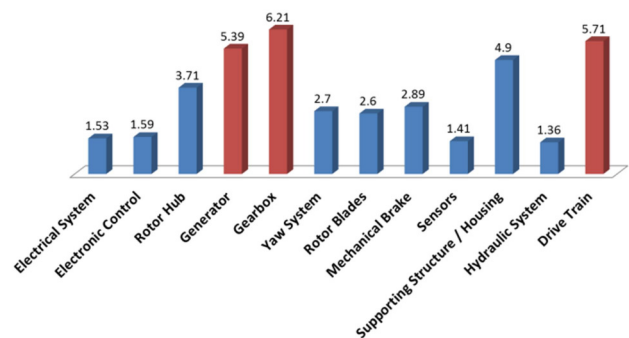


Fig. 1 Downtime for different wind turbine components. Drive train related components are shown in red

This paper investigates UMP generation due to eccentricity in an electrical generator. The paper presents results obtained through modelling work and describes a novel experimental test rig design to verify the simulation results. An accurate generator model will form the basis of a UMP induced bearing wear model which will take into account of wave and tidal current loadings on the drive train. This will allow novel design and control strategies to be developed in order to minimise unbalanced forces from the generator and reduce bearing failures due to wear.

II. ROTOR ECCENTRICITY & UNBALANCED FORCES

Wave energy converters and tidal current turbines experience large changes in torque, inducing rapid acceleration. This is caused by the variable nature of the energy resource resulting in a constantly changing wave force or turbulent flow. This has a profound effect on the structural performance of turbine blades in oscillating water columns and tidal current turbines. Although large-scale devices are being installed, there are still uncertainties over the significance of different loads imposed on turbine blades and the effect of flow turbulence. The influence of onset turbulence on horizontal-axis turbine loads has been investigated in [4]. It shows that, similarly to horizontal-axis

wind turbines, longitudinal turbulence intensity dominates for both extreme and fatigue loads. Studies have also shown that fatigue loading on tidal current turbine blades is sensitive to wave action where larger waves significantly reduce the fatigue stress margin at the blade root [5]. The combined action of flow turbulence and wave action increases the likelihood of turbine blades experiencing intermittent radial forces that propagate along the drive train. This produces a bending moment that can lead to temporary or, in the case of extreme loadings, permanent misalignment of the drive train. This in turn leads to rotor eccentricity at the electrical generator.

Rotor eccentricity is a non-uniform air gap between the rotor and stator of an electrical machine due to the displacement of the rotor in the radial direction. Electrical generators exhibit low-level rotor eccentricity due to a degree of tolerance and wear.

There are two types of eccentricity: static eccentricity, where the rotor rotates on its own axis but not in the centre of the stator bore, and dynamic eccentricity, where the rotor is centred in the stator bore but does not rotate on its own axis. This is shown in Fig. 2.

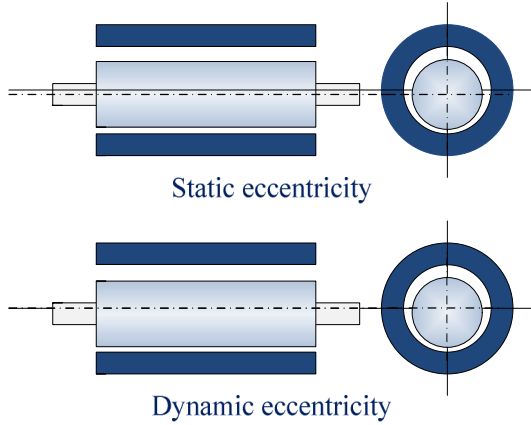


Fig. 2 Diagram showing static and dynamic eccentricity. The solid line shows the centre of the stator bore and the dotted line shows the rotor axis of rotation.

The bottom diagram in Fig. 2 shows one particular type of dynamic eccentricity, where the eccentricity is uniform along the axial rotor length. In some cases, it is possible to have eccentricity that varies along the rotor shaft and also possible for static and dynamic eccentricity to co-exist. For static eccentricity, the air gap is a function of the stator position and can be expressed as:

$$g_{se}(\theta) = g - e \cdot \cos \theta \quad (1)$$

where g is the normal mechanical air gap when the rotor is concentric. For dynamic eccentricity, the air gap is a function of the rotational angle and can be described as:

$$g_{dy}(\theta) = g - e \cdot \cos(\theta - \omega_r t) \quad (2)$$

where ω_r is the rotor angular velocity.

The asymmetric air gap between the rotor and the stator creates a radial force that pulls the rotor further off-centre, towards the smaller air gap where there is a concentration of flux. This radial force is known as unbalanced magnetic pull. Electrical generators are typically designed with a narrow air gap to reduce losses; hence any slight deviation in the rotor position can generate UMP.

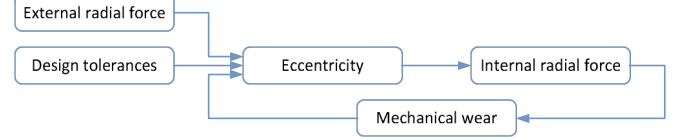


Fig. 3 Block diagram of the cause and effect of rotor eccentricity in relation to bearing wear

Fig. 3 shows a block diagram of the cause and effect of rotor eccentricity. As previously mentioned, design tolerances and external radial forces such as loadings on turbine blades lead to rotor eccentricity. Eccentricity causes an internal radial force (UMP) to be generated, which increases mechanical wear on bearings. Bearing wear subsequently leads to additional eccentricity, which further increases the internal radial force. Bearings are designed to operate within a particular load range and have an estimated lifetime based on this. Operation outside of this range due to addition loadings from UMP would greatly reduce bearing lifetime. Dynamic loads caused by varying radial forces also have an adverse effect on lifetime.

Although there have been many papers published on UMP in electrical machines, with some dating back more than a century, the theory of UMP was initially developed in 1955 by Summers, using rotating field components [6]. Subsequently, Frohne explained that UMP is generated as a result of the interaction between two magnetic fields with pole-pair numbers differing by one [7]. This has been shown through graphical representation in [8]. Calculation of UMP in induction machines, as used in a number of well-known wave and tidal devices, is particularly complicated compared with other types of machine. This is due to the presence of a secondary circuit, which requires the calculation of rotor currents and consideration of parallel circuits in the rotor. It has proven to be a challenge to develop models that are able to cope with air gap variation and therefore provide accurate calculations. However, modern computational power offers the prospect of using finite element methods to aid UMP calculation and to understand the key factors in UMP generation. Finite elements can also be used for verification in the development of analytical models.

It is important to note that previous literature on UMP has focused on machines running as motors in steady-state operation. Machines in wave and tidal devices run as generators and often at variable speed. Hence the modelling of transient UMP is as important as steady-state UMP shown in previous literature. Although this work does not consider transient UMP, it forms part of the overall development of a UMP-induced bearing wear model for wave and tidal devices.

Although measurement of UMP is considered to be a difficult task, advancements in transducer technology and signal conditioning techniques have made the measurement process a realistic and worthwhile proposition. Measurement of UMP through direct or indirect methods is important, particularly for generators located offshore, as it can be used as part of a control strategy for UMP reduction and also help to improve machine design. Reduction of UMP is only possible if the initial measurement is accurate.

III. MODELLING

For cylindrical objects, such as the rotor of a generator, the Maxwell stress tensor in the radial direction can be expressed as:

$$\sigma_r = \frac{b_n^2 - b_t^2}{2\mu_0} \quad (3)$$

where b_n is the normal magnetic flux density, b_t is the tangential magnetic flux density in the air-gap and μ_0 is the permeability of free space. The tangential component is conventionally negligible. Therefore, the total radial magnetic force applied on the rotor of a generator is given as:

$$F_r = L \int_0^{2\pi} \frac{b_n(\theta, t)^2}{2\mu_0} d\theta \quad (4)$$

This force can be neglected when the rotor is perfectly concentric but need to be taken into account when there is rotor eccentricity as a considerable UMP force will be induced.

In order to illustrate the effect of rotor eccentricity and armature reaction on the induced UMP in permanent magnet machines, an 11kW slotted permanent magnet machine has been modelled and simulated. The parameters of the machine are shown in Table I.

TABLE I
PERMANENT MAGNET MACHINE PARAMETERS

Rated power	11 kW
Axial length	111 mm
Nominal voltage	330 V
Nominal current	23.3 A
Nominal air gap	1.65 mm
Air gap diameter	104 mm
Magnet height	5 mm
Number of slots	36
Number of poles	8
Number of turns	10

Two-dimensional finite element method (FEM) open-source software was used to study the effect of rotor eccentricity on the magnetic flux density in the generator air gap and hence the induced UMP for different levels of eccentricity. The software is particularly suitable for solving

low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains [9]; therefore, no-load cases for permanent magnet machines are simple to model and simulate. However, loading cases are more complex to simulate and required additional instruction using a scripting language. The meshing size is controllable and 30° minimum meshing angle has been chosen for accurate analysis. A two-dimensional diagram of the studied machine showing the flux density lines is illustrated in Fig. 4.

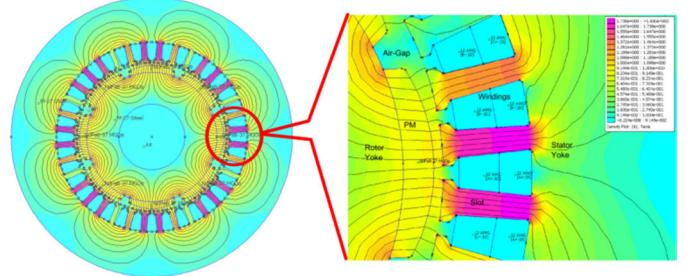


Fig. 4 Cross-section of an 11kW permanent magnet machine with concentric rotor

In order to investigate the armature reaction effect on the induced UMP, results are presented for the no-load case and also for loading up to 30A.

A. No-load case

It is shown in [10] that an increase in static eccentricity causes an increase in the magnitude of the permeance in one side of the air gap and a decrease on the opposite side. That leads to a corresponding change in the magnitude of the air gap flux density which induces UMP. The relationship between static rotor eccentricity and UMP for the studied generator using FEM software is linear as shown in Fig. 5.

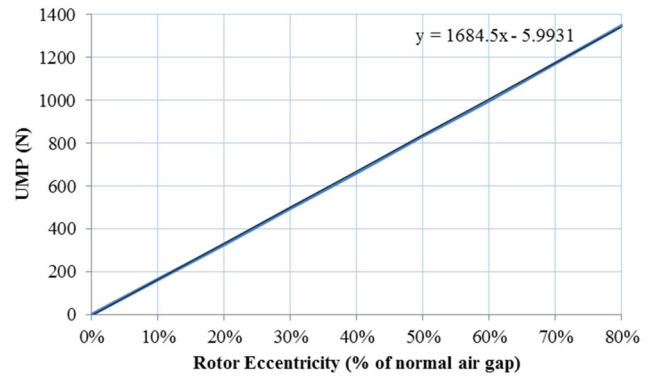


Fig. 5 Graph of UMP versus rotor eccentricity for the modelled generator

The flux density distribution in the air gap with 40% eccentricity is shown in Fig. 6. The rotor has been horizontally displaced on the x-axis; therefore, the flux density magnitude in the figure varies with the circumferential distance. The slotting effect on the flux density distribution is clear in this figure as a wave distortion whereas the flux density wave is smooth in slotless permanent magnet machines.

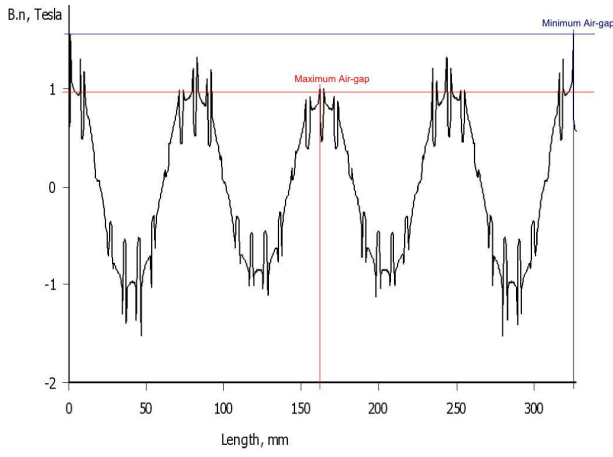


Fig. 6 Flux density distribution in the air gap with 40% eccentricity

B. Loaded case

The effect of armature reaction on UMP in both parallel and series winding connection cases with both static and dynamic eccentricities seems to be very small and can be neglected as shown in Fig. 7. As the open-source FEM software does not support the simulation of both the stator loading 3-phase alternating currents and the rotor permanent magnets simultaneously, Fig. 7 has been obtained by loading the stator coils using instantaneous direct currents with different amplitudes. The direct current amplitude for each coil has been calculated and applied automatically for each rotor rotation step using the LUA scripting language. For each instantaneous rotor position, a new mesh and UMP calculation has been implemented. The spatial UMP variation shown in Fig. 8 is mainly due to the slotting effect and is the cause of slight vibrations and noise in the machine.

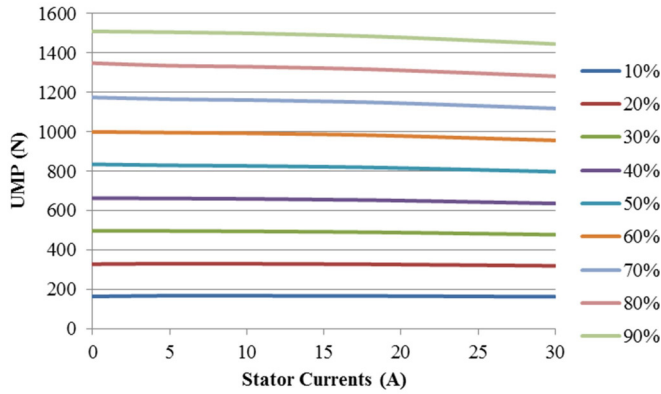


Fig. 7 The effect of armature reaction on UMP, with different load cases and different rotor eccentricities.

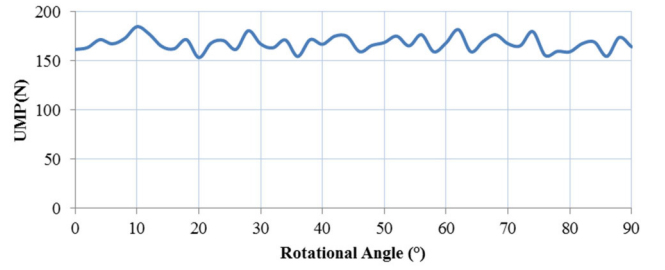


Fig. 8 Spatial UMP variations for one electrical cycle with 10% eccentricity and 5A stator current

IV. EXPERIMENTAL TEST RIG DESIGN

To verify the results obtained from FEM modelling in section III, experimental work is required. Hence this section describes an experimental test rig design to introduce rotor eccentricity and measure unbalanced forces in the generator. Fig. 9 shows a block diagram of the experimental test rig. The test generator is driven by a motor with a torque transducer interfacing the two machines to measure the input mechanical power. The output of the generator is connected to a 3-phase load to control the power output from the generator. Measurement data from the torque transducer, force sensors, and power analyser all feed into a data acquisition unit.

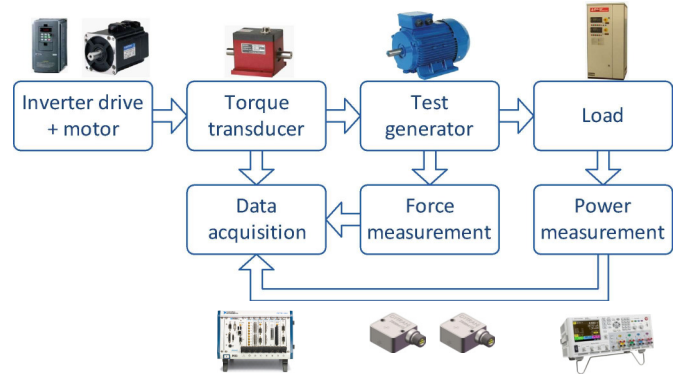


Fig. 9 Block diagram of the experimental test rig for generator force measurement

A. Creating Eccentricity

In order to measure unbalanced forces acting on the rotor, an eccentricity needs to be introduced into the generator. For experimental purposes this can be created by physically moving the rotor in the radial direction relative to the stator. Electrical machines typically have a rotor which is held in position by end caps mounted to the main body of the machine. Bearings in each end cap allow the rotor to rotate freely inside the machine. To create eccentricity the rotor must be able to move independently of the stator; hence it is necessary to mount the rotor independently of the main body. This can be achieved by removing the end caps and mounting the rotor on external bearings.

After mounting the rotor on external bearings, eccentricity can be created by adjusting the rotor or the stator position. As

the test generator is driven by a motor to emulate the input mechanical power from a wave or tidal current converter, any adjustments for eccentricity should be made only to the stator. This allows the rotor to remain aligned to the rest of the drivetrain regardless of the amount of eccentricity created. Adjusting the vertical displacement of the stator is the simplest way of creating eccentricity. This can be achieved by inserting shims, tens of micrometres in thickness, between the main body of the generator and the platform to which it is secured. Hence, the addition or removal of each shim increments or decrements a fixed amount from the overall displacement of the stator. Alternatively, an adjustable micro-positioning platform can be used to lower or raise the height of the generator body. In both methods the value of eccentricity created must be known, which requires accurate linear displacement measurement.

B. Force Measurement

Unbalanced magnetic pull acts on the rotor in the direction of the narrowest air gap. This force needs to be measured with transducers that convert force into an electrical signal. The most widely used force transducers use either strain gauge or piezoelectric-based technology. Strain gauge load cells utilise the elastic range of the cell material to measure force. Strain gauges bonded to the material (such as steel or aluminium) change in electrical resistance as the material deforms under an applied force. Hence strain gauge load cells require deformation in order to measure force. This is not desirable for measuring generator forces due to eccentricity as deformation causes a change in the air gap which leads to a change in eccentricity.

Piezoelectric force transducers require less deformation to generate an electrical signal. They utilise crystalline materials that generate an electric charge on the surface when a force is applied. They are inherently stiffer than strain gauge load cells and have a higher frequency response, which is more suitable for dynamic measurements. However, they are less suitable for static measurements compared to strain gauge load cells due to charge leakage in the charge amplifiers. Multiple piezoelectric crystals can be stacked to create a multi-component force transducer.

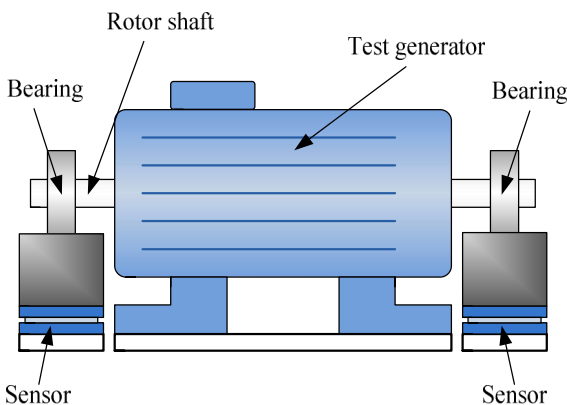


Fig. 10 Diagram showing the rotor mounted on external bearings and force sensors beneath the bearing units

Piezoelectric force transducers were chosen due to their superior stiffness and characteristics under dynamic loading. Whilst the use of multiple single-axis transducers would have been a more cost-effective option, there is complexity in mounting multiple transducers without each transducer interfering with the force measurement of others. Hence multi-axis transducers were chosen for the test rig. From Newton's third law it can be deduced that UMP can be measured on the rotor or the stator given that the forces should be equal and opposite in nature. Hence, transducers can be mounted under the rotor or the stator, supporting the full weight of either in order to measure the unbalanced force.

Fig. 10 shows a diagram of the rotor mounted separately from the stator on external bearings, with force transducers beneath the bearing units.

C. Actual Test Rig

Fig. 11 shows a photograph of the experimental test rig. The photograph shows the test generator with the end cap removed, showing the stator end windings and the rotor. The original bearing is still located on the rotor shaft although it does not perform any function here. The larger external bearing is shown with one of the piezoelectric force transducers supporting the bearing housing. Note that during operation the external bearing would be positioned closer to the original bearing in order to minimise flexibility in the rotor shaft, which may cause oscillations.

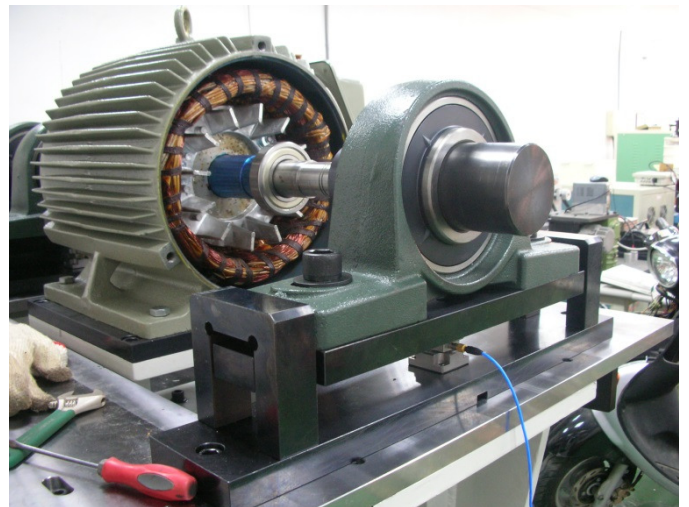


Fig. 11 Diagram showing the rotor mounted on external bearings and force sensors beneath the bearing units

As shown in Fig. 11, a single force transducer supports the bearing housing. This arrangement was part of a preliminary setup to determine if the test rig was capable of using a single sensor at each end rather than two sensors, which would increase the overall cost. Given the shape of the bearing housing, it would be difficult to prevent oscillations from occurring even if the force transducer was perfectly centred with the centre of the rotor shaft. This would be a particular problem when the generator is operating at high speed. A single sensor could be utilised if the width of the bearing

housing was similar to that of the force transducer. However, this would require a shaft thickness which is smaller than that of the original rotor shaft.

V. CONCLUSIONS

This paper has presented an FEM model of a permanent magnet generator to investigate UMP due to stator rotor eccentricity. It has also presented a design for an experimental test rig to measure unbalanced forces due to eccentricity and verify simulation results. Most of the work presented in the paper is transitional but nonetheless a necessary step towards the understanding of the effect of unbalanced forces on bearings in wave and tidal devices and how wear and failure can be mitigated through design and control.

ACKNOWLEDGMENT

The authors would like to thank the Engineering and Physical Sciences Research Council in UK and the National Science Council in Taiwan for funding this work.

REFERENCES

- [1] P.J. Tavner, *Offshore Wind Turbines- Reliability, Availability & Maintenance*, Institution of Engineering and Technology, 2012.
- [2] S. Faulstich, B. Hahn, and P.J. Tavner, "Wind turbine downtime and its importance for offshore deployment," *Wind Energy*, vol. 14, pp. 327-337, 2010.
- [3] J.K.H. Shek, D.G. Dorrell, M. Hsieh, D.E. Macpherson, and M.A. Mueller, "Reducing Bearing Wear in Induction Generators for Wave and Tidal Current Energy Devices," IET Renewable Power Generation Conference, Edinburgh, UK, 2011.
- [4] I.A. Milne, R.N. Sharma, R.G.J. Flay, and S. Bickerton, "The Role of Onset Turbulence on Tidal Turbine Blade Loads," Australian Fluid Mechanics Conference, Auckland, New Zealand, 2010.
- [5] G.A. McCann, "Tidal current turbine fatigue loading sensitivity to waves and turbulence – a parametric study," European Wave and Tidal Energy Conference, Porto, Portugal, 2007.
- [6] E.W. Summers, "Vibration in 2-Pole Induction Motors Related to Slip Frequency," *Transactions of the American Institute of Electrical Engineers - Power Apparatus and Systems, Part III*, vol. 74, pp. 69-72, 1955.
- [7] H. Frohne, "The practical importance of unbalanced magnetic pull, possibilities of calculating and damping it," *Conti Elektro Berichte*, vol. 13, pp. 81-92, 1967.
- [8] D.G. Dorrell, "Experimental behaviour of unbalanced magnetic pull in 3-phase induction motors with eccentric rotors and the relationship with tooth saturation," *IEEE Transactions on Energy Conversion*, vol. 14, pp. 304-309, 1999.
- [9] *Finite Element Method Magnetics* (Version 4.2), 2010 [Online] Available: <http://www.femm.info/Archives/doc/manual42.pdf>
- [10] J.R. Cameron, W.T. Thomson, and A.B. Dow, "Vibration and current monitoring for detecting airgap eccentricity in large induction motors," *Electric Power Applications, IEE Proceedings B*, vol. 133, no. 3, pp. 155-163, 1986.